(12) UK Patent Application (19) GB (11) 2 382 127 (13) A

(43) Date of A Publication 21.05.2003

(21) Application No 0224419.2

(22) Date of Filing 21.10.2002

(30) Priority Data
(31) 0125189 (32) 19.10.2001 (33) GB

(51) INT CL[7]
F25B 9/14, F17C 13/00, G01R 33/3815

(52) UK CL (Edition V)
F4H HG13
U1S S2048

(56) Documents Cited
GB 2330194 A
GB 2310486 A
GB 2329701 A
US 6112527 A

(58) Field of Search
UK CL (Edition V) F4H
INT CL[7] F25B
Other: ONLINE DATABASES: WPI EPODOC JAPIO

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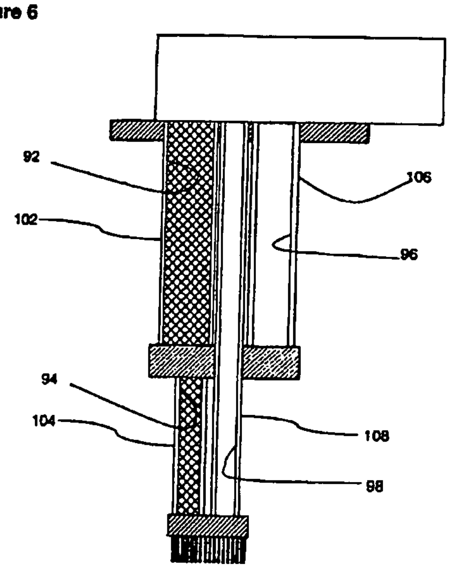
(54) Abstract Title
Pulse tube refrigerator

(57) A pulse tube refrigerator for use in recondensing cryogenic liquids, in particular, in a magnetic resonance imaging system, comprises a pulse tube refrigerator located in an outer jacket (not shown). Each of one or more pulse tubes (96,98) and regenerator tubes (92,94) of the pulse tube refrigerator is covered with an insulating outer sleeve (102,104,106,108) to reduce heat transfer between the respective tubes and between the respective tubes and the outer jacket. The tube wall of the pulse tube or regenerator tube and the tube wall forming the respective outer sleeve wall are preferably of the same material, such as stainless steel or titanium. The space inside the sleeve may be evacuated or partially evacuated with getter material eg activated charcoal, carbon paper or zeolite, or the space inside the sleeve may be filled with powder insulation eg perlite, or with hollow glass spheres. The tube wall forming the outer sleeve wall may be corrugated to provide strength.

Figure 6



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

This print takes account of replacement documents submitted after the date of filing to enable the application to comply with the formal requirements of the Patents Rules 1995

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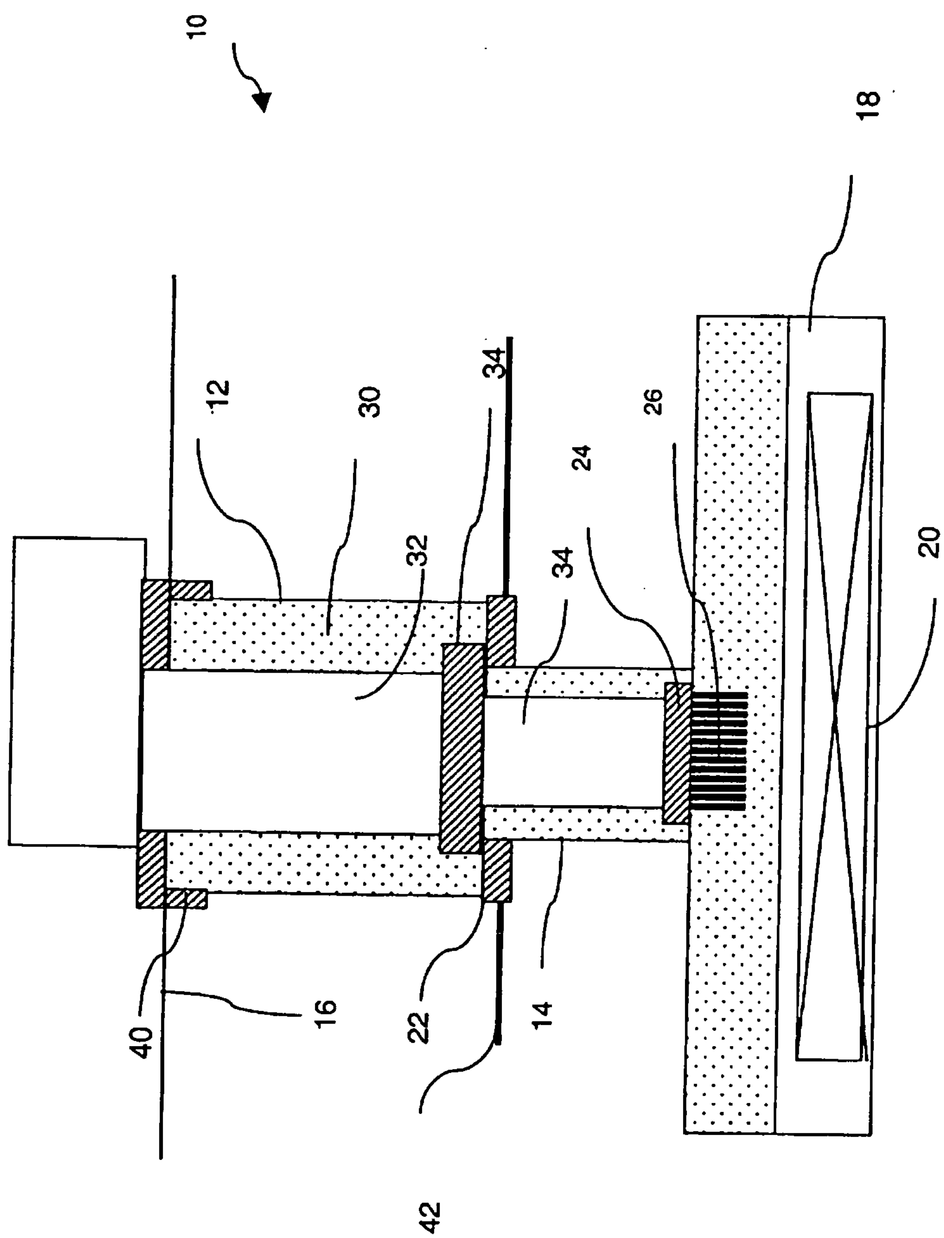


Figure 1

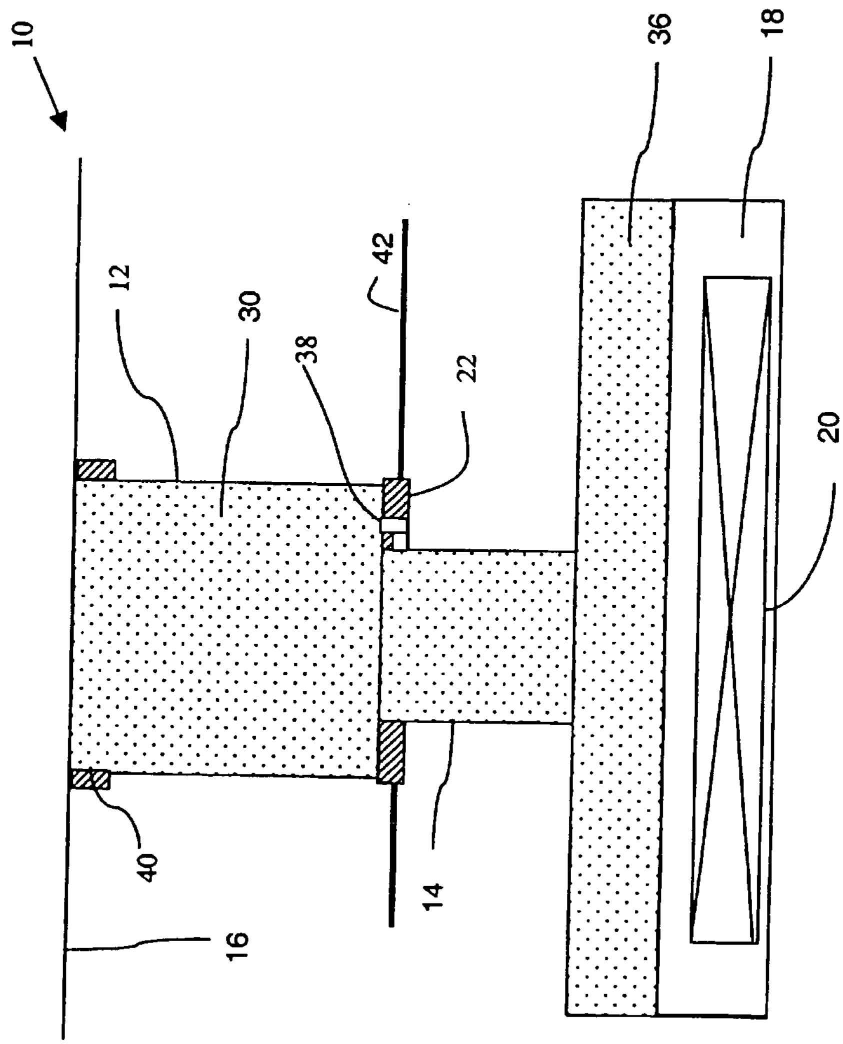


Figure 1A

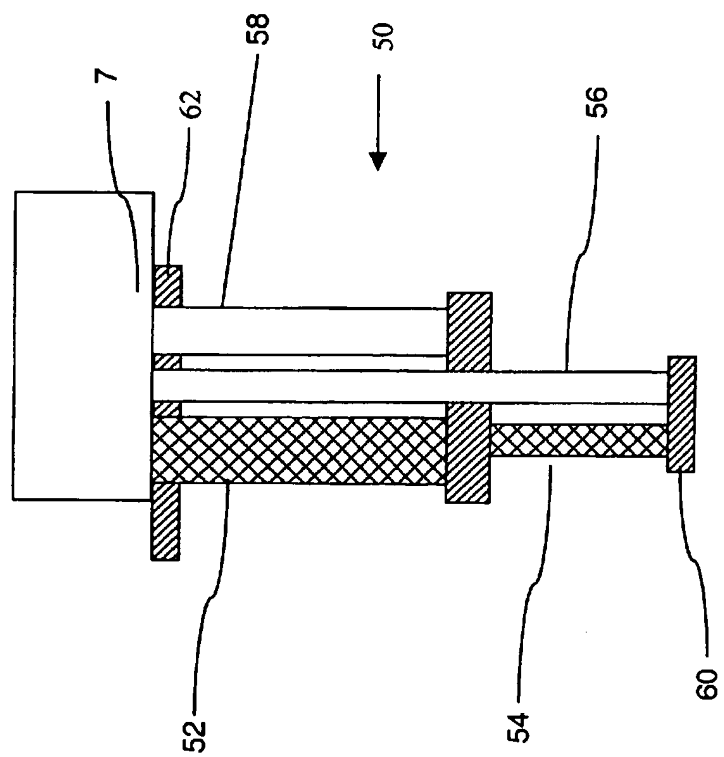


Figure 2

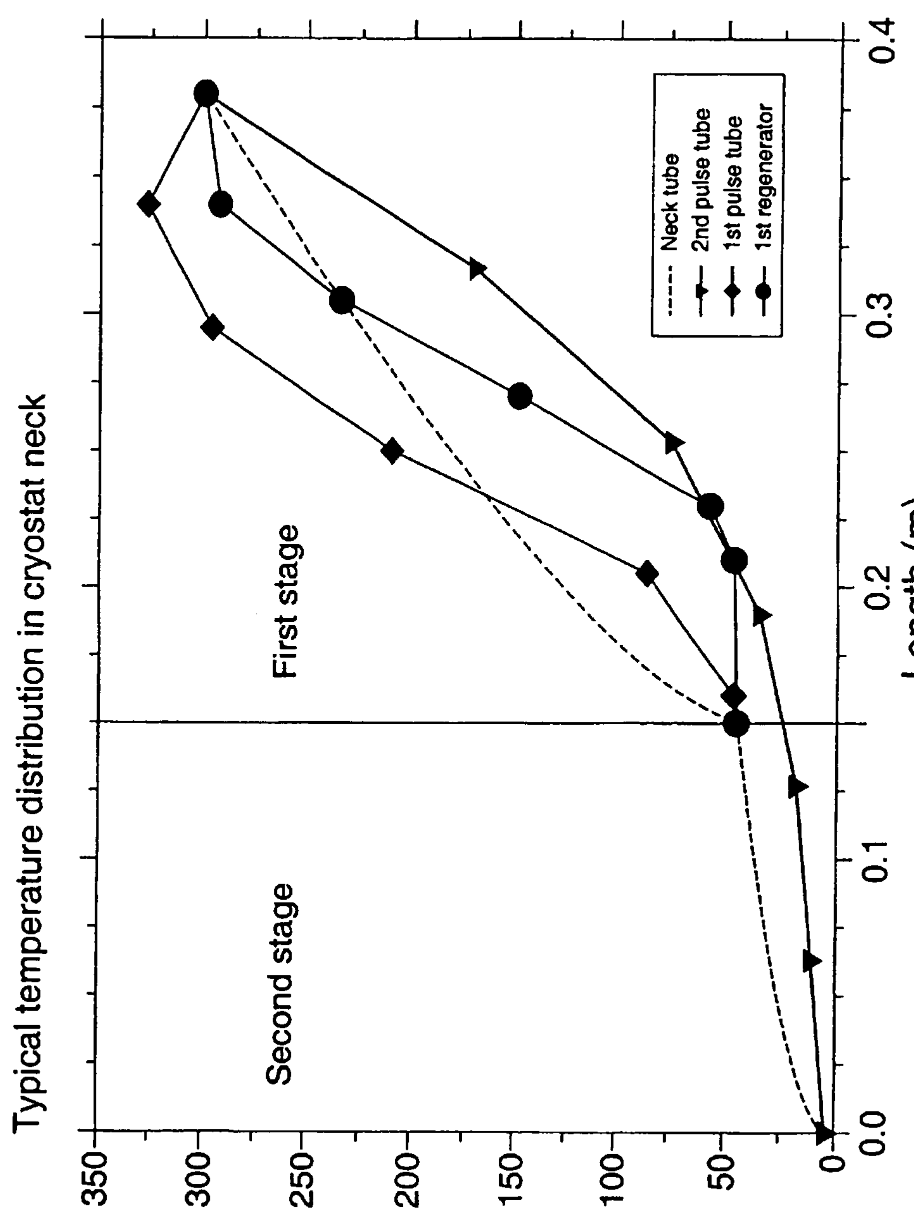

Typical temperature distribution in cryostat neck
Temperature (K)
Length (m)
First stage
Second stage
Neck tube
2nd pulse tube
1st pulse tube
1st regenerator
0
50
100
150
200
250
300
350
0.0
0.1
0.2
0.3
0.4

Figure 3

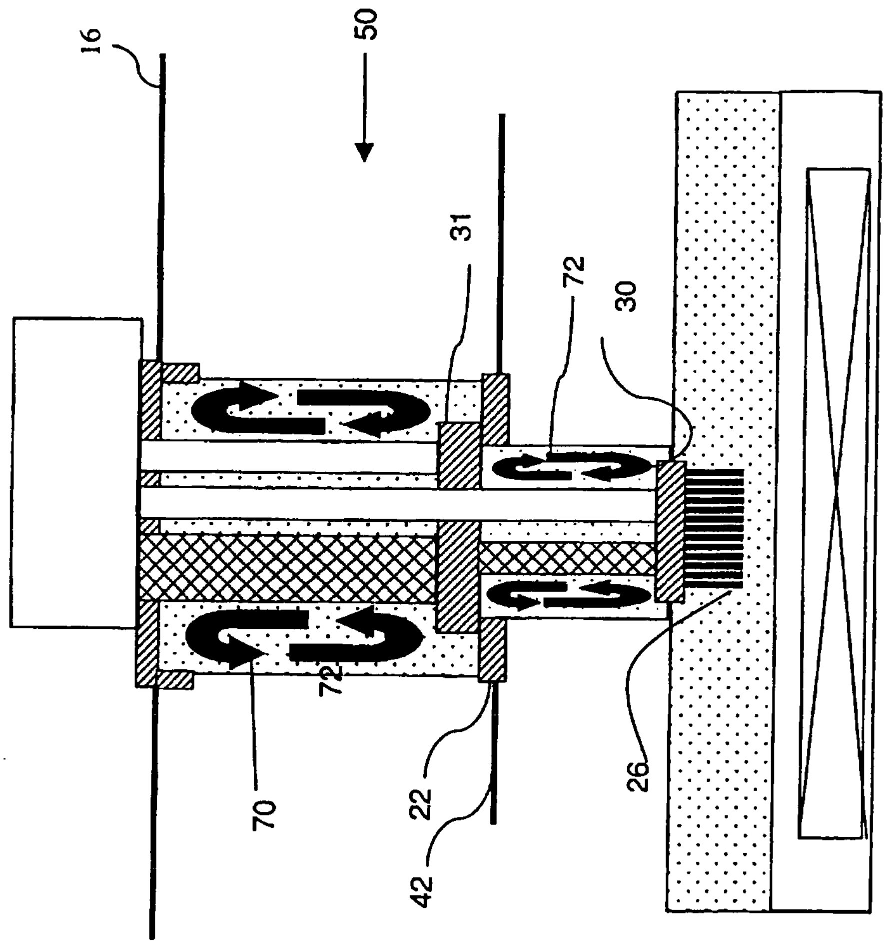


Figure 4

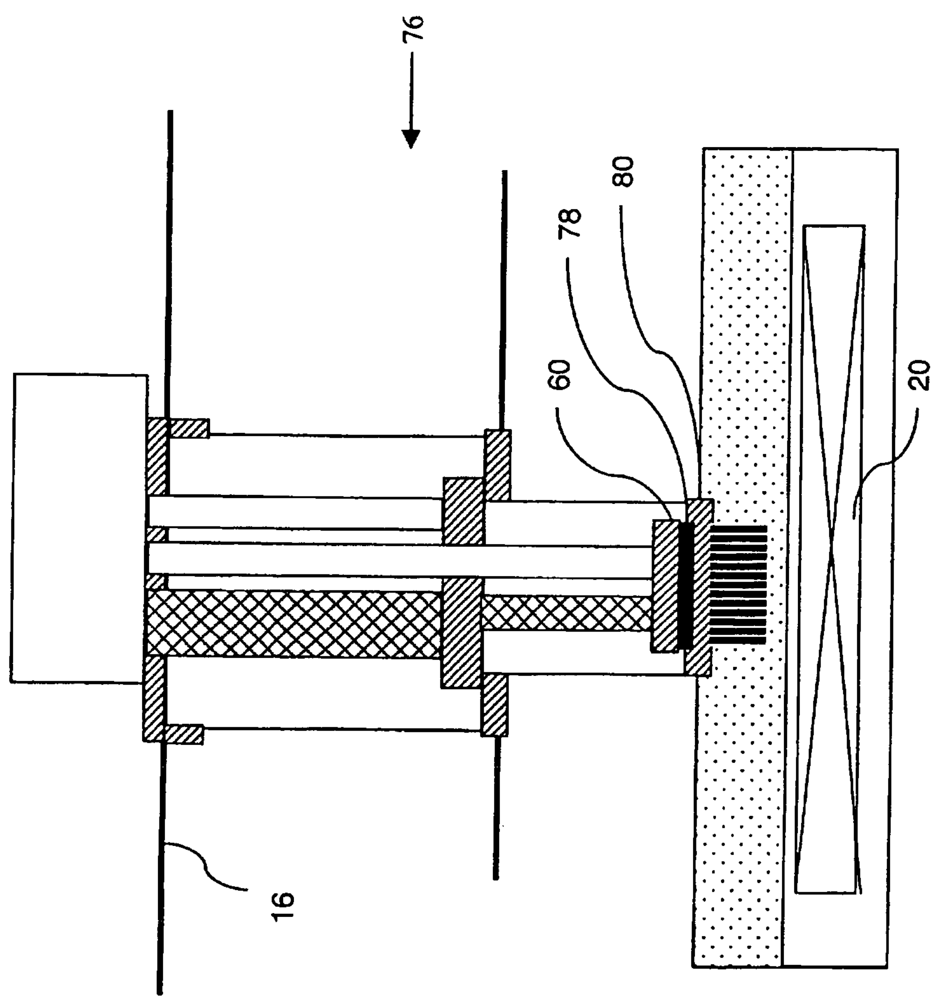


Figure 5

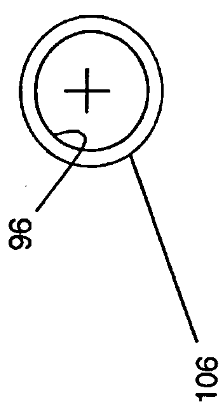


Figure 6A

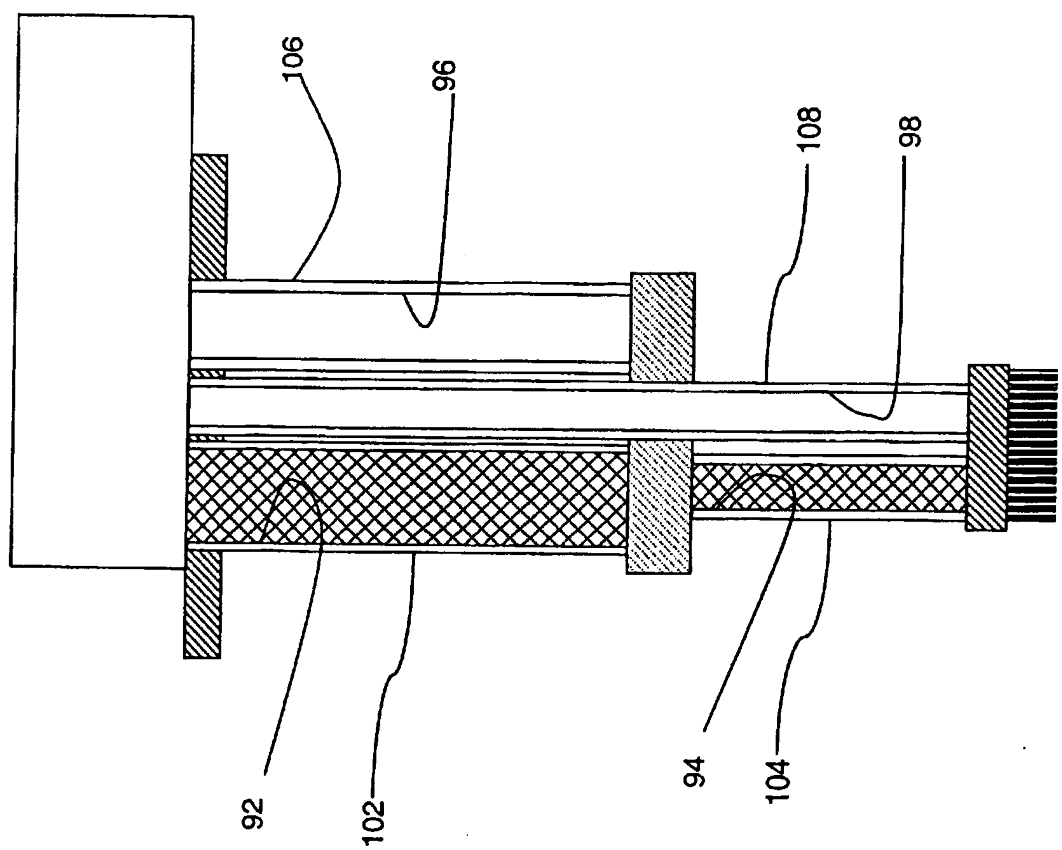


Figure 6

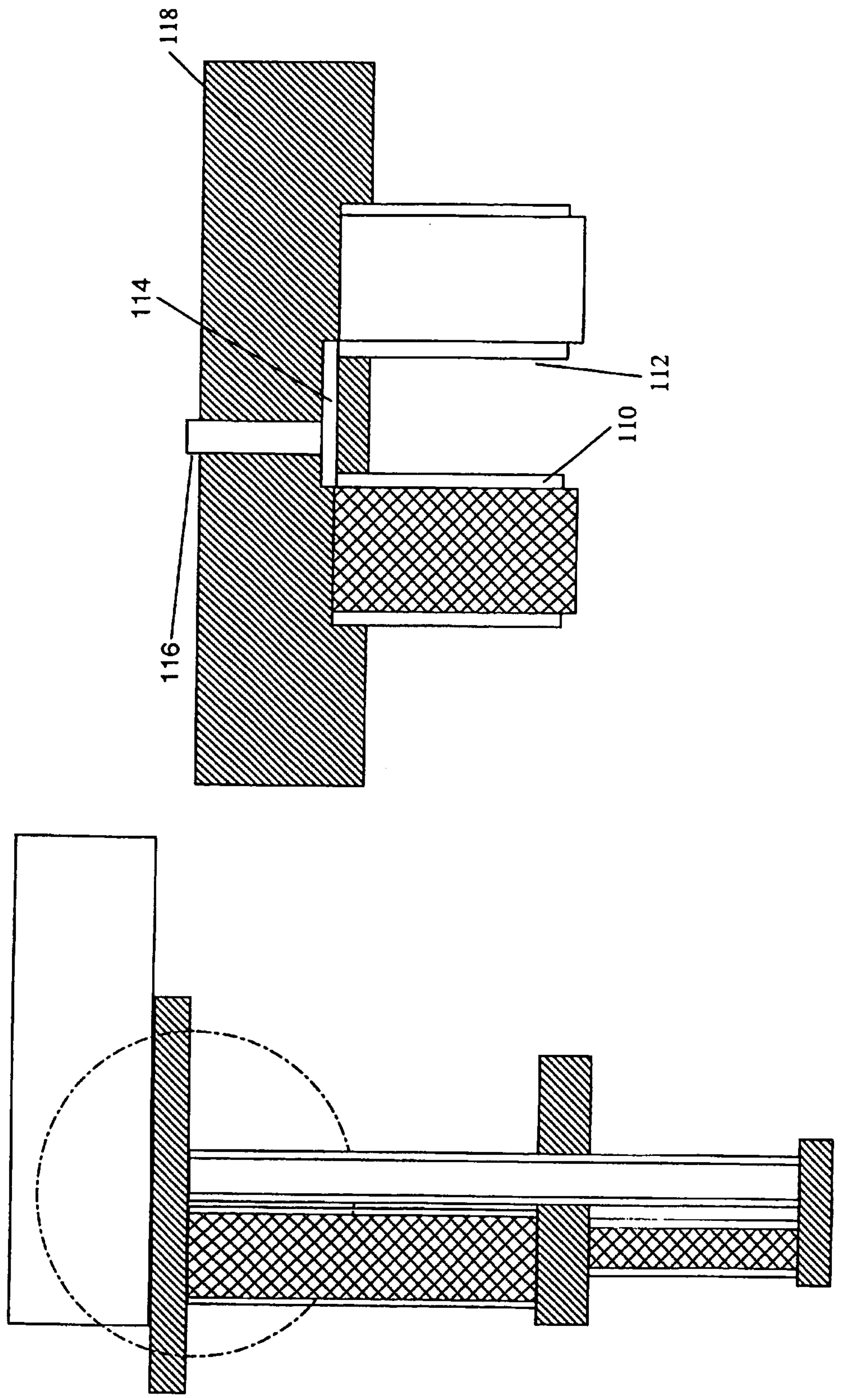


Figure 7

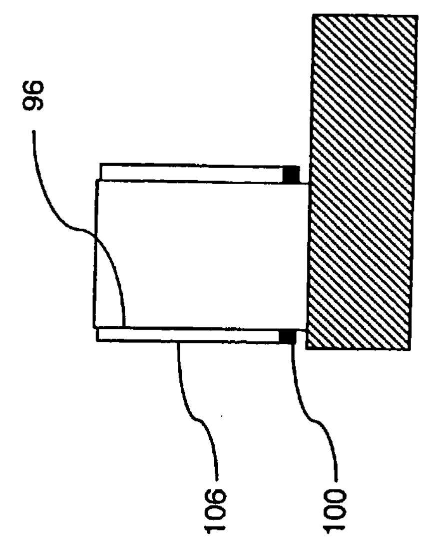


Figure 8

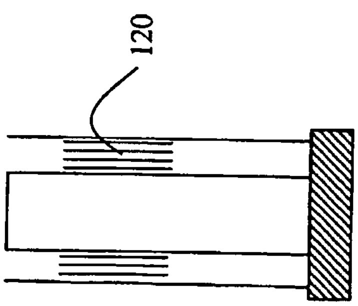


Figure 9A

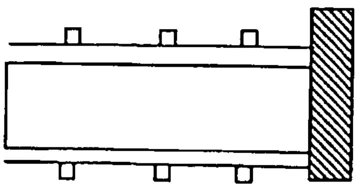


Figure 9B

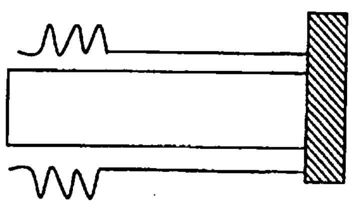


Figure 9C

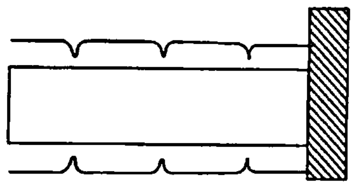


Figure 9D

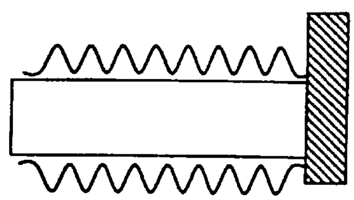


Figure 9E

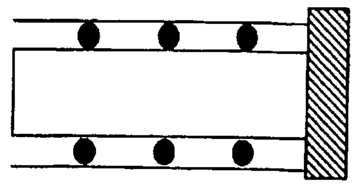


Figure 9F

Figure 10A

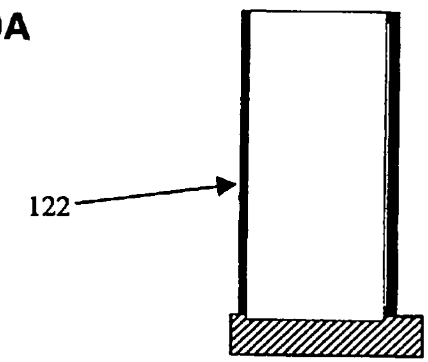


Figure 10B

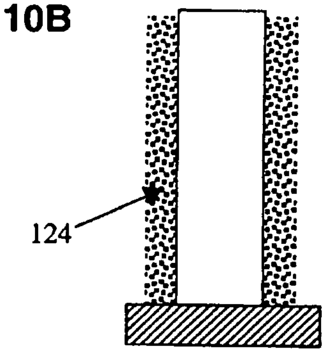


Figure 10C

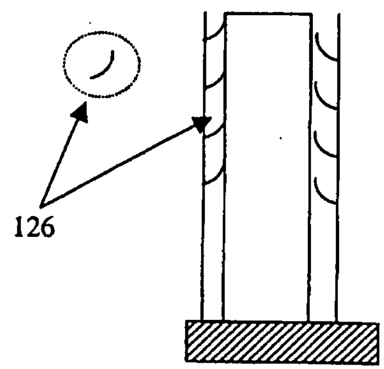
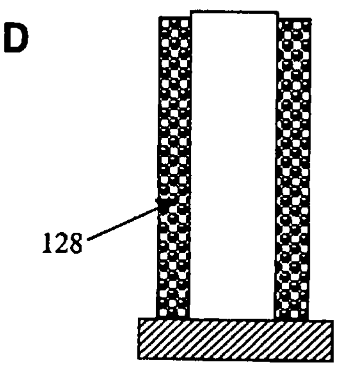


Figure 10D



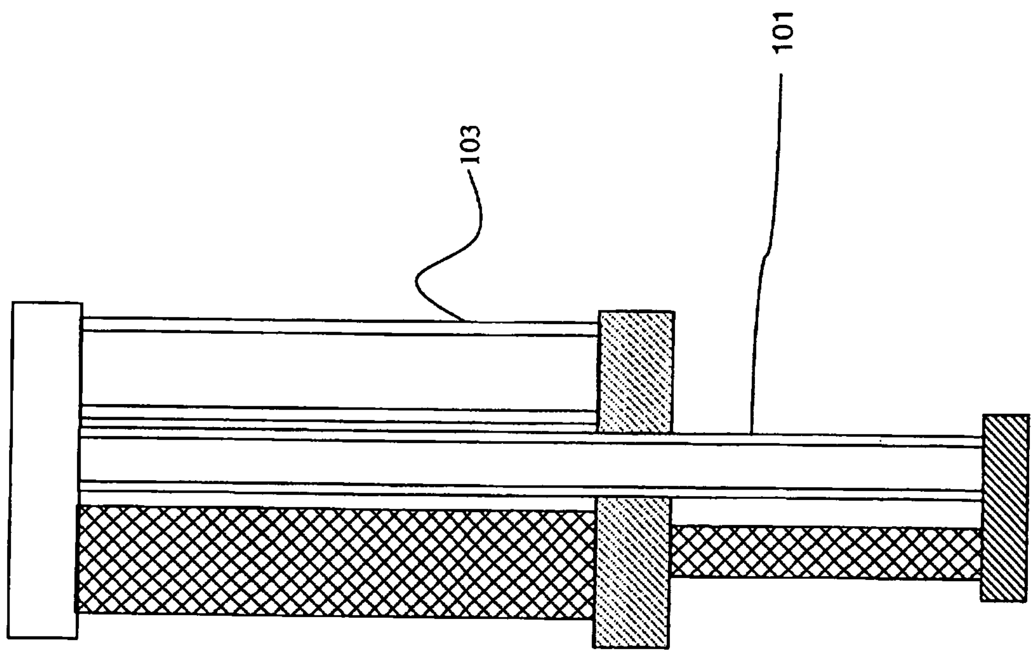


FIGURE 11

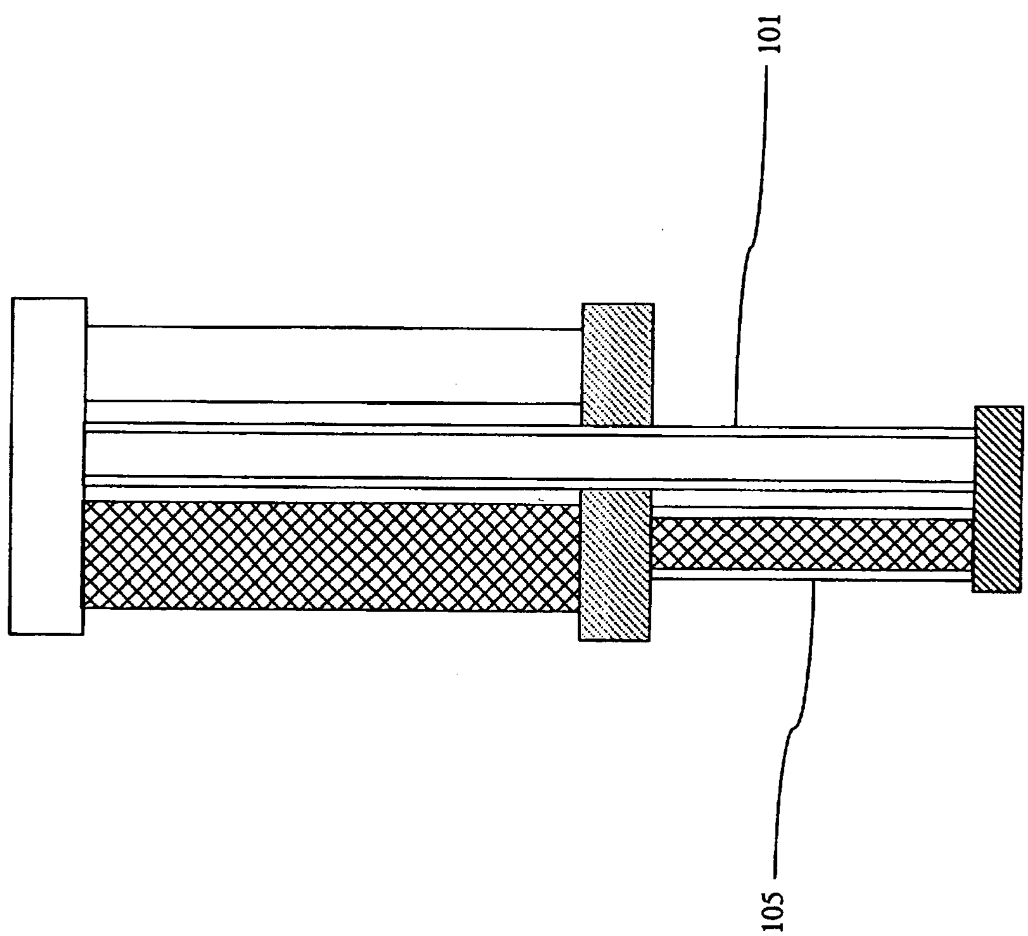


FIGURE 12

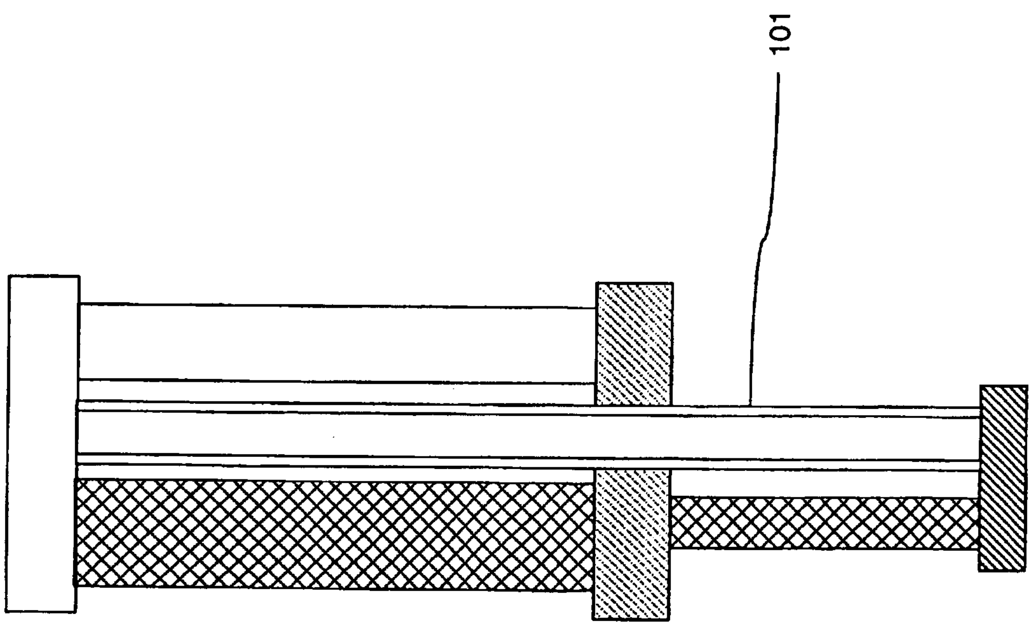


FIGURE 13

A PULSE TUBE REFRIGERATOR SLEEVE

Field of the invention

The present invention relates to pulse tube refrigerators for recondensing cryogenic liquids. In particular, the present invention relates to the same for magnetic resonance imaging systems.

Background to the Invention

In many cryogenic applications components, e.g. superconducting coils for magnetic resonance imaging (MRI), superconducting transformers, generators, electronics, are cooled by keeping them in contact with a volume of liquefied gases (e.g. Helium, Neon, Nitrogen, Argon, Methane). Any dissipation in the components or heat getting into the system causes the volume to part boil off. To account for the losses, replenishment is required. This service operation is considered to be problematic by many users and great efforts have been made over the years to introduce refrigerators that recondense any lost liquid right back into the bath.

As an example of prior art, an embodiment of a two stage Gifford McMahon (GM) coldhead recondenser of an MRI magnet is shown in Figure 1. In order for the GM coldhead, indicated generally by 10, to be removable for service or repair, it is inserted into a sock, which connects the outside face of a vacuum vessel 16 (at room temperature) to a helium bath 18 at 4K. MRI magnets are indicated at 20. The sock is made of thin walled stainless steel tubes forming a first stage sleeve 12, and a second stage sleeve 14 in order to minimise

heat conduction from room temperature to the cold end of the sock operating at cryogenic temperatures. The sock is filled with helium gas 30, which is at about 4.2K at the cold end and at room temperature at the warm end. The first stage sleeve 12 of the coldhead is connected to an intermediate heat station of the sock 22, in order to extract heat at an intermediate temperature, e.g. 40K-80K, and to which sleeve 14 is also connected. The second stage of the coldhead 24 is connected to a helium gas recondenser 26. Heat arises from conduction of heat down through the neck, heat radiated from a thermal radiation shield 42 as well as any other sources of heat for example, from a mechanical suspension system for the magnet, (not shown) and from a service neck (also not shown) used for filling the bath with liquids, instrumentation wiring access, gas escape route etc. A radiation shield 42 is placed intermediate the helium bath and the wall of the outer vacuum vessel.

The second stage of the coldhead is acting as a recondensor at about 4.2K. As it is slightly colder than the surrounding He gas, gas is condensed on the surface (which can be equipped with fins to increase surface area) and is dripped back into the liquid reservoir. Condensation locally reduces pressure, which pulls more gas towards the second stage. It has been calculated that there are hardly any losses due to natural convection of Helium, which has been verified experimentally provided that the coldhead and the sock are vertically oriented (defined as the warm end pointing upwards). Any small differences in the temperature profiles of the Gifford McMahon cooler and the walls would set up gravity assisted gas convection, as the

density change of gas with temperature is great (e.g. at 4.2. K the density is 16kg/m^3; at 300 K the density is 0.16kg/m^3). Convection tends to equilibrate the temperature profiles of the sock wall and the refrigerator. The residual heat losses are small. Figure 1A shows a corresponding view without coldhead 32, 34 in place. In greater detail, the intermediate section 22 shows a passage 38 to enable helium gas to flow from the volume encircled by sleeve 14. The latter volume is also in fluid connection with the main bath 36 in which the magnet 20 is placed. Also shown is a flange 40 associated with sleeve 12 to assist in attaching the sock to the vacuum vessel 16.

When the arrangement is tilted, natural convection sets up huge losses. A solution to this problem has been described in US Patent, US-A-5,583,472, to Mitsubishi. Nevertheless, this will not be further discussed here, as this document relates to arrangements which are vertically oriented or at small angles (<30°) to the vertical.

It has been shown that Pulse Tube Refrigerators (PTRs) can achieve useful cooling at temperatures of 4.2K (the boiling point of liquid helium at normal pressure) and below (C. Wang and P.E. Gifford, Advances in Cryogenic Engineering, 45, Edited by Shu et a., Kluwer Academic/Plenum Publishers,2000, pp.1-7). Pulse tube refrigerators are attractive, because they avoid any moving parts in the cold part of the refrigerator, thus reducing vibrations and wear of the refrigerator. Referring now to Figure 2, there is shown a PTR 50 comprising an arrangement of separate tubes, which are joined together at heat stations. There is one regenerator tube 52, 54 per stage, which is filled with solid materials in different forms (e.g.

meshes, packed spheres, powders), that act as heat buffer and exchange heat with the working fluid of the PTR (usually He gas at a pressure of 1.5-2.5 MPa). There is one pulse tube 56, 58 per stage, which is hollow and used for expansion and compression of the working fluid. In two stage PTRs, the second stage pulse tube 56 usually links the second stage 60 with the warm end 62 at room temperature, the first stage pulse tube 58 linking the first stage 64 with the warm end.

It has been found, that PTRs operating in vacuum under optimum conditions usually develop temperature profiles that are significantly different across the tubes and also from what would be a steady state temperature profile in a sock. This is shown in Figure 3.

Another prior art pulse tube refrigerator arrangement is shown in Figure 4 wherein a pulse tube is inserted into a sock, and is exposed to a helium atmosphere wherein gravity induced convection currents 70, 72 are set up in the first and second stages. The PTR unit 50 is provided with a cold stages 31, 33 which are set in a recess in an outer vacuum container 16. A radiation shield 42 is provided which is in thermal contact with first sleeve end 22. A recondenser 26 is shown on the end wall of second stage 33. If at a given height the temperatures of the different components are not equal, the warmer components will heat the surrounding helium, giving it buoyancy to rise, while at the colder components the gas is cooled and drops down. The resulting thermal losses are huge, as the density difference of helium gas at 1 bar changes by a factor of about 100 between 4.2 K and 300 K. The net cooling power of a PTR might be e.g. 40 W at 50

K, and 0.5W to 1 W at 4.2K. The losses have been calculated to be of the order of 5-20W. The internal working process of a pulse tube will, in general, be affected although this is not encountered in GM refrigerators. In a PTR, the optimum temperature profile in the tubes, which is a basis for optimum performance, arises through a delicate process balancing the influences of many parameters, e.g. geometries of all tubes, flow resistivities, velocities, heat transfer coefficients, valve settings etc. (A description can be found in Ray Radebaugh, proceedings of the 6th International Cryogenic Engineering Conference, Kitakkyushu, Japan, 20-24 May, 1996, pp22-44).

Therefore, in a helium environment, PTRs do not necessarily reach temperatures of 4 K, although they are capable of doing so in vacuum. Nevertheless, if the PTR is inserted in a vacuum sock with a heat contact to 4K through a solid wall, it would work normally. Such a solution has been described for a GM refrigerator (US Patent US-A-5,613,367 to William E. Chen, GE) although the use of a PTR would be possible and be straightforward. The disadvantage, however, is that the thermal contact of the coldhead at 4K would produce a thermal impedance, which effectively reduces the available power for refrigeration. As an example, with a state of the art thermal joint made from an Indium washer, a thermal contact resistance of 0.5 K/W can be achieved at 4 K (see e.g. US-A –5,918,470 to GE.). If a cryocooler can absorb 1W at 4.2K (e.g. the model RDK 408 by Sumitomo Heavy Industries) then the temperature of the recondensor would rise to 4.7K, which would reduce the current carrying capability of the superconducting wire drastically. Alternatively, a stronger cryocooler

would be required to produce 1 W at 3.7 K initially to make the cooling power available on the far side of the joint.

Figure 5 shows an example of such a PTR arrangement 76. The component features are substantially the same as shown in Figure 4. Thermal washer 78 is provided between the second stage of the PTR coldhead and a finned heat sink 80. A helium-tight wall is provided between the thermal washer and the heat sink.

Object of the invention

The present invention seeks to provide an improved pulse tube refrigerator.

Statement of the Invention

In accordance with a first aspect of the invention, there is provided a PTR in a sock, which connects room temperature to a cryogenic reservoir; characterised in that each of one or more pulse tubes and regenerator tubes of the PTR is covered with an insulating sleeve, whereby to reduce heat transfer between the tubes and between the tubes and the surrounding sock. The sleeve may completely cover the pulse tubes and regenerator tubes or just in part. The PTR can be helium filled.

The convection problem can thus be efficiently overcome, without compromising the functionality and general geometry of the PTR. In particular it has been found, how the amount of insulation effort can be minimised by reducing the insulation to the pulse tubes, being most affected by convection by the internal working process.

Brief description of the figures

The invention may be understood more readily, and various other aspects and features of the invention may become apparent from consideration of the following description and the figures as shown in the accompanying drawing sheets, wherein:

Figure 1 shows a two stage Gifford McMahon coldhead recondenser in a MRI magnet;

Figure 1A shows the coldhead of Figure 1 without the recondenser tubes;

Figure 2 shows a PTR consisting of an arrangement of separate tubes, which are joined together at the heat stations;

Figure 3 shows a temperature profile in a sock;

Figure 4 shows a pulse tube is inserted into a sock;

Figure 5 shows a prior art example of a pulse tube with a removable thermal contact;

Figure 6 shows a first embodiment of the invention;

Figure 6A shows a cross-section of the first embodiment;

Figure 7 shows an open path of the vacuum space of the tubes;

Figure 8 details wall tube sleeving;

Figure 9A-F, show different mechanical forms of the vacuum sleeve;

Figures 10A - D show further embodiments of the invention;

Figure 11 shows an arrangement with only pulse tubes insulated;

Figure 12 shows only the second stage tubes (pulse tube and regenerator) with insulation; and

Figure 13 shows an example where only the second stage pulse tube is insulated.

Detailed description of the invention

There will now be described, by way of example, the best mode contemplated by the inventors for carrying out the invention. In the following description, numerous specific details are set out in order to provide a complete understanding of the present invention. It will be apparent, however, to those skilled in the art, that the present invention may be put into practice with variations from the specific embodiments.

Referring now to Figure 6, there is shown a first embodiment of the invention, wherein a 2-stage PTR arrangement 90 is shown. An outer sleeve (not shown) is provided over the whole arrangement of tubes. Regenerator tubes 92, 94 and pulse tubes 96, 98 are provided with insulating sleeves identified 102, 104 and 106, 108 respectively.

Figure 6A shows a cross-section through the PTR arrangement. An inner wall, the tube wall 96 is surrounded by a sleeve 106. Conveniently the tube inner wall and the sleeve are manufactured simultaneously, preferably from the same material, such as stainless steel or titanium. The space inside may be evacuated or partially evacuated with getter materials inserted therein to enhance the removal of gaseous elements within the tube wall-sleeves. Such getter materials are preferably placed at the cold end and can comprise

activated charcoal, carbon paper - which can be wound around the tubes, and zeolithes, for example. The insulation quality can be further enhanced by wrapping Superinsulation TM foil into a vacuum gap, if present.

Whilst all four sleeves can be evacuated separately through individual ports (not shown), with reference to Figure 7; the vacuum spaces 110, 112 of the tubes can lead to an open path 114 to an evacuation port 116 in the top plate at 300K in a section of a coldhead 118.

Figure 8 shows detailed view of an insulated tube comprising a pulse tube 96 with a sleeve 106 which are connected in a vacuum tight fashion by brazed/welded connection 100. The double walled tubes can be evacuated during manufacture by joining them in a vacuum process, for example by vacuum brazing or electron beam welding.

The insulating gap between the tubes need not be evacuated during manufacture and can initially have air present. During cooldown, the air will condense and eventually freeze towards the cold end of each stage (40 K and 4.2 K respectively). Getter materials can be used and are particularly helpful to reduce gaseous components. Insulation quality will, however, be compromised but no pump out lines or other fillings necessary for vacuum processes will be required, enabling simple manufacture and reducing the number of thermal paths in contact with the tubes.

In Figures 9A-F, different mechanical forms of the vacuum sleeve are shown. In Figure 9A the oversleeve comprises a straight tube with reference number 120 indicating the presence of

superinsulation between the tube and sleeve. The tube wall is thick enough to withstand the surrounding helium pressure during evacuation without any buckling.

In figure 9B, in order to reduce the parasitic heat load due to the extra wall cross-section, the tube wall is extremely thin and a number of reinforcing rings are present in order to strengthen the sleeve.

In Figure 9C the tube is partially corrugated to provide anti-buckling strength, whilst in figure 9D the tube is fully corrugated. In figure 9E circumferentially swaged indentations deliver added strength. In Figure 9F there is shown a tube with an inner structure of rings or a nylon thread to provide anti- buckling strength and also to interrupt any internal convection paths. Nylon and similar plastics have very low thermal conductivities.

A further variation is shown in Figure 10A, wherein, for manufacturing convenience, the sleeve and wall 122 are unitary, of a low conductivity material and there is no vacuum space. Alternatively the tube has an epoxy oversleeve, or an inner epoxy liner is placed inside a stainless steel tube. All usual production processes can be applied like winding layers and subsequent curing. Insulating tape can be applied on the outside of the tube, e.g. foamed PTFE tape 124, or different types of insulating foams, felts, superinsulation etc can be applied to the outside of the tubes as shown in Figure 10B.

In Figure 10C convection in a helium filled gap in a double walled tube is suppressed by the presence of lip seals 126. In Figure 10D, a non vacuum sleeve or low vacuum sleeve is filled with loose insulation materials, e.g. powder insulation like perlite or hollow glass

spheres 128, which can be internally evacuated or even covered with a reflective film, say of sputtered aluminium to reduce radiation.

The insulation for individual tube can differ among each other, any combination of insulation and partial insulation can be applied. For example, the first stage can be covered with a vacuum insulation, the second with free-standing foam insulation. Also, in some applications it can be sufficient to insulate just the first stage or the second stage only. Figure 11 shows only the pulse tubes 101, 103 with sleeves; Figure 12 shows pulse tubes 101 and regenerated tube 105 with sleeves and Figure 13 shows only pulse tube 101 with a sleeve.

While most applications cryogenic temperatures, e.g. at or around 4K for MRI apparatus operate with two stage coolers, the same technology can also be applied to single stage coolers or three and more stage coolers.

CLAIMS:

1. A pulse tube refrigerator PTR in a sock, which connects room temperature to a cryogenic reservoir;

characterised in that each of one or more pulse tubes and regenerator tubes of the PTR is covered with an insulating sleeve, whereby to reduce heat transfer between the tubes and between the tubes and the surrounding sock.

2. A PTR according to claim 1 wherein the sock is filled with helium.

3. A PTR according to claim 1 or 2 wherein each insulating sleeve comprises an outer wall spaced from an inner tube.

4. A PTR according to claim 1 or 2 wherein the sleeve and tube are integral.

5. A PTR according to claim 1 or 2 wherein the sleeve comprises a material selected from the group comprising superinsulation, thinsulate, foam, and the like and wherein the sleeve is placed around the tube.

6. A PTR according to claim 3 wherein the space between the sleeve and the inner tube is filled with an insulating material.

7. A PTR according to any one of claims 1 - 5 wherein the walls of the sleeve are corrugated.

8. A PTR according to claim 3 wherein the space within the sleeve is in a state of vacuum.

9. A PTR according to any one of claims 1 - 8 wherein the PTR recondenser comprises part of a magnetic resonance imaging apparatus.

10. A PTR according to any one of claims 1 - 9 wherein only a second stage pulse tube is insulated.

11. A PTR according to any one of claims 1 - 9 wherein only second stage tubes comprising a pulse tube and a regenerator are insulated.

12. A PTR according to any one of claims 1 - 9 wherein only pulse tubes are insulated.

13. A method of using a pulse tube refrigerator PTR in a sock, which connects room temperature to a cryogenic reservoir, the method comprising the step of insulating one or more pulse tubes and regenerator tubes with an insulating sleeve whereby to reduce heat

transfer between the tubes and between the tubes and the surrounding sock.

14. A method according to claim 13 wherein the one or more tubes comprise an insulating sleeve spaced from an inner tube.

15. A method according to claim 13 or 14 wherein the PTR comprises part of a magnetic resonance imaging apparatus.

The Patent Office 15 -

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Application No:	GB 0224419.2	**Examiner:**	M C Monk
Claims searched:	All	**Date of search:**	13 March 2003

Patents Act 1977 : Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance	
A		GB 2330194 A	OXFORD MAGNET TECHNOLOGY LTD Pulse tube refrigerator (8) surrounded by neck tube (6).
A		GB 2329701 A	OXFORD MAGNET TECHNOLOGY LTD Pulse tube refrigerators (20,22) both appear of a double-walled nature.
A		GB 2310486 A	HE HOLDINGS INC A concentric pulse tube having an insulation tube (19) disposed around the central pulse tube.
A		US 6112527	SIEMENS AKTIENGESELLSCHAFT Regenerator (6) has an encasing tube (6a); pulse tube (7) has an encasing tube (7a).

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{V}:

F4H

Worldwide search of patent documents classified in the following areas of the IPC^{7}:

F25B

The following online and other databases have been used in the preparation of this search report:

WPI, EPODOC, JAPIO